

Title: Overflows, Vortices and Surface Mixing in Ocean Dynamics: Theory, Modeling and Experiment

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Abstract: The dynamics of Earth's oceans plays a pivotal role in determining global climate variations from the seasonal effects of El Nino to long-term trends arising from CO₂-induced global warming and melting polar ice caps. Predicting climate change requires sophisticated models run on the world's most powerful computers. Much of the input for such models is obtained from fundamental assumptions about large-scale fluid dynamics and from field data with very limited spatial resolution. Thus, there are large uncertainties in global ocean circulation models that hamper the ability to make accurate predictions. To address this complex problem, we propose using a unique combination of precise laboratory experiments guided by real ocean observations, high-resolution direct numerical simulation, and careful modeling to elucidate the small-scale fluid dynamics upon which the large-scale models depend and to thereby improve a major weakness in existing ocean circulation models. The first part of our proposal concerns the formation of cold, dense water in the North Atlantic, a process that helps drive the millennial-scale thermohaline circulation. The work proposed here will put us squarely at the front of such efforts. In the second, we will quantitatively explore the transfer of energy and potential vorticity in a forced, rotating parabolic flow that approximates atmospheric and oceanic conditions - a problem at the forefront of understanding the physics of inverse and forward energy cascade in these planetary-scale systems. Third, we will investigate the mixing and transport of density in a surface driven stratified layer, approximating wind-driven surface turbulent mixing of the upper ocean layers. The distinguished set of researchers on our team are uniquely suited to this particular challenge of advancing our capabilities to correctly simulate large scale fluid flows in the ocean. Because of the need for sophisticated experiments we have allocated NK per year in our budget for equipment.

Proposal Duration: 3 years

Proposed Funding:

Year	FY2004	FY2005	FY2006
Operating	1100 K	1100 K	1100 K
Capital	100 K	50 K	

Institutional Goals and Objectives:

The atmosphere/ocean system is an important, compelling example of a complex problem requiring a full suite of computational, experimental and theoretical tools to predict its future evolution with confidence. In particular, large-scale model simulations require input of fundamental physics and experimental benchmarks derived from both field and laboratory-based experiments. The capability to do such experiments and to simulate on fine scales using massively-parallel computers has converged today to offer a unique opportunity at Los Alamos to couple state-of-the-art experiments that can obtain high-resolution flow field data with direct numerical simulation (DNS) and predictive large-scale global climate models (GCMs). The result will be major strengthening of the predictive power of GCMs and a novel example of how complex systems can be attacked. The issues we will address are forefront fundamental problems in geophysical fluid dynamics and vitally important for advancing GCMs.

Our goal is to use an interdisciplinary team to explore complex problems in ocean dynamics from understanding the fundamental physical processes to developing theoretical models and implementing the results into GCM codes. Our approach is to use scaled laboratory experiments, direct numerical simulations, theoretical modeling, and efficient inclusion into GCMs. Our experiments have been carefully chosen to investigate important regimes in global climate science. In these experiments we will exploit our recent high-density particle tracking and temperature field measurement capabilities combined with novel analysis tools to fully characterize the stably-stratified shear flows and vortex-dominated geophysical flows. Direct numerical simulations on LANL computers will provide a wealth of data to compliment the experiments. Results from these more fundamental models will be used to motivate and constrain theoretical models that we will develop based on scaling and self-similarity. Lastly, these new subgrid models will be used in LANL's OGCMs and their advantage demonstrated.

Science and Technology Objectives

Our proposal has three parts: dense overflows, rotating shallow water in a beta-plane geometry, and surface-driven mixing of a stably-stratified system. These systems are important and poorly understood both from the first principles and from predictive large-scale modeling.

A) *Dense overflows*: At the edge of the Greenland-Iceland-Norwegian seas dense arctic water overflows a ridge and spills down steep inclines in a thin density-driven plume until it reaches the deep abyss of the Atlantic Ocean [2]. On the way down it mixes with the ambient water, creating "North Atlantic Deep Water" (NADW) that makes up 70% of the world ocean and whose density properties play a critical role in the thermohaline circulation. Recent data from programs such as the World Ocean Circulation Experiment (WOCE) indicate that ocean models are lacking in their representation of deep-water properties and circulation, difficulties attributable to the overflows. Misrepresenting NADW formation sets the stage for centuries-long ocean model drifts that seriously interfere with attempts to simulate human-induced climate change. Current ocean circulation models do not capture the physics of these overflows, predicting too little or too much mixing, nor can in situ experiments resolve crucial issues of mixing and entrainment within these stably-stratified shear flows. We will interface with important external members of the DOME working group by providing detailed physics behind the small-scale mixing in overflows. We will: Investigate experimentally a high-Reynolds number, stably-stratified boundary layer with velocity-field, passive-scalar, and thermal-field measurements; Perform DNS of dense water overflows for realistic experimental configurations to provide quantities needed for modeling; Construct a theoretical model of overflows that mixes

using data from experiments and DNS; Implement and test the model in a GCM.

B) *Potential vorticity evolution in a forced, rotating beta-plane*: The formation of large-scale structures in the atmosphere and oceans involves a poorly understood transfer of energy from small-scale thermal motion to large-scale circulation. Using an unique experimental configuration we will study fundamental transfer mechanisms of forced, quasi two-dimensional shallow water flows in a near parabolic geometry. Small-scale turbulent forcing induced by magnet arrays builds larger scale structures through vortex merger. With finite damping due to Ekman layers and continual forcing, complex potential-vorticity structures can form, mimicking the formation of meandering Jet-Stream-like Rossby waves. Using such an experimental system we will: Investigate the formation and mechanisms of turbulent transfer using filter-approach and flow-topology diagnostics on velocity-field data; Perform DNS and planetary scale runs using the GCMs of rotating flows and relate them to conditions in Earth's atmosphere and oceans.

C) *Surface mixing in a stratified layer*: Wind currents at the sea surface induce turbulence and larger-scale vertical circulation that transports salinity and mixes the upper layers of the ocean. A quantitative understanding of this important phenomenon does not exist and we propose experiment, theory and simulation to elucidate the fundamental physics of upper surface mixing. We will: Measure mixing in an experiment with a discrete density discontinuity - a light fluid over a heavier one - in which a combination of surface turbulence and large-scale circulation is driven by surface jets and influenced by cell aspect ratio; Develop and test theoretical descriptions of turbulent entrainment and transport in the density gradient direction; develop a new model for the GCMs, including implementation and validation.

Expected Payoff/Impact

In the last decade LANL has taken a leadership role in global climate modeling of the ocean. But state-of-the-art GCMs (here and elsewhere) do not include non-hydrostatic dynamics, which creates road-blocks for making progress in simulating climate change. GCMs must rely on models to account for the effects of small scale dynamics. Currently these models are based on best guesses, simply because the problems have yet to be studied quantitatively. The impact of the multi-disciplinary research proposed here gives LANL's climate modeling program a key push into the next decade of scientific leadership by filling the gap between fundamental small scale physics and its impact on the scales important for climate-scale dynamics in three key areas. It allows us to take advantage of LANL's expertise and computing resources to solve important scientific problems related to successfully understanding the global climate and impact DOE's Climate Change Prediction Program, energy use policy and carbon cycle modeling, all of which are part of the DOE mission. It supports DOE's program in Carbon Sequestration which depends critically on adequate simulations of deep ocean circulation. Similarly, carbon cycle modeling and ocean carbon uptake depend on surface mixed layer processes. Further, the highly collaborative nature of this work, integrating experimental, theoretical and computational efforts, will enhance the Laboratory's capabilities in managing the type of integrated efforts that are also needed in stockpile stewardship. We expect that, given the importance of this problem, it will bring international visibility to LANL's efforts in environmental sciences. Finally, the capabilities and reputation of our scientific team is outstanding with expertise in experiment, simulation and theory, with publications in high profile journals such as Science, Nature, & Phys. Rev. Lett., and in specialized journals from J. Fluid Mech. to J. Phys. Ocean., reflecting our interdisciplinary team of oceanographers, applied mathematicians, physicists and fluid dynamicists, and with recognition as Laboratory and professional society Fellows. (For references see www.lanl.gov/orgs/mst/MST10/fluid_dynamics).